Acoustic Detection of EAS in DUMAND

John G. Learned
Department of Physics and Astronomy, University of Hawaii

Abstract

Measurement of the primary cosmic ray energy which produces deeply penetrating muons would enable studies of primary cosmic ray composition. It is suggested herein to utilize the downgoing acoustic pulse produced by an Extensive Air Shower hitting the ocean surface to make crude observation of the total energy deposition. The surface area covered could be thus enormous compared to existing EAS arrays, around 100 km^2. The trigger would be from the DUMAND array itself after observation of high energy muons, or muon bundles, or perhaps only for muons from a given direction. The acoustic pulse will arrive from a known direction with a delay of about 3 seconds. Since the DUMAND array will incoporate at least 100 hydrophones we can anticipate a gain of at least 100 in signal-to-noise from processing. Further gains can be realized from matched filtering for the known pulse profile. The technique will surely work at some energy, the question is at what threshold. While detailed calculations are required, it is suggested herein that under optimal conditions the threshold might be as low as 10^{18} eV, but probably is higher. Unknown mechanisms might lower the threshold, but real ocean noise may make it higher. We conclude that while EAS acoustic detection in DUMAND seems to be marginal because the expected rate at 10^{18} eV is low, it still may be worth pursuing with further calculations, and in low cost field studies in prototype DUMAND installations.

Submitted to the Proceedings of the "US-Japan Joint Seminar on Cosmic Ray muon and Neutrino Physics/Astrophysics using Deep Underground/Underwater Detectors", Tokyo, Japan, June 1986

18 June 1986

HDC-8-86

Introduction

There is strong motivation to find a technique to enable the measurement on an event by event basis of the primary cosmic ray particle's energy that leads to muons traversing DUMAND. It is well known that studies of composition of cosmic rays would greatly benefit from the tagging of the primary energy along with observation of the muon multiplicity underearth. While the deep muon multiplicity itself does reflect the composition, the convolution of the multiplicity over the incoming energy spectrum greatly degrades the discrimination of models. This problem is compounded by the uncertain energy dependance of the composition and uncertainties in the interaction modelling. Suggestions have been made at several DUMAND Workshops to tether shallow subsurface arrays above the muon detector or to deploy a Fly's Eye type of detector for the purpose of obtaining a measure of the primary energy.

Op Herein the suggestion is made to study the downgoing acoustic pulse produced by the EAS depositing energy at the ocean surface. Because of laboratory tests we know that charged particles traversing water do generate an acoustic pulse, but unfortunately the amplitude is very small. Previous calculations, mostly having to do with hadronic cascades, indicate that the threshold for detection is of the order of 10^{16} eV at distances of the order of 1 km. The present situation is somewhat more difficult because the deposition is over a relatively large region. We may hope however that we will gain by being able to search at a predetermined time and direction for a known waveshape. This is possible because we can choose to initiate the search only when some predetermined signal is observed in the DUMAND array. We may, for example, wish to trigger upon a cluster of muons, a very high energy muon, or on muons coming from a predetermined direction.

The potentially great advantage of this acoustic method is that our surface detection area may be enormous compared with installations which depend upon the coincidence between a necessarily restricted size of surface array and an underground detector. DUMAND is both much larger than any other contemplated underearth detector in area (by at least 100x), and could have an effective surface area of the order of 100 km^2 (if we assume that we are able to make observations out to a zenith angle of 45^0 or so). For calculating the rate from cosmic rays, the appropriate measure is the acceptance, the product of solid angle and area, of the combined system. This would be about 1/2 km^2 sr for DUMAND, and may be compared with the Homestake installation which has an acceptance of about 10^{-6} of this value. There is another advantage in the ability to track a potential source (at least one that passes within 20^0 or so of the zenith) continuously for as much as 8 hours per day.

Estimate of Signal-to-Noise

For the moment I will only make a quick estimate of the signal magnitude and the signal-to-noise ratio. We will then discuss possibile gains and losses from this crude calculation. The detailed calculation will have to take account of the shower lateral and energy distribution, ocean wave perturbation of the surface, and details of the energy loss of electrons and muons hitting the surface. However, for estimating purposes it is fortunate that the mechanism of pressure pulse generation in water only depends upon the total thermal energy deposition per unit volume, at least when observed at distances large compared to the size of the source region. The most important parameter is the radial extent of the deposition region as seen from the observation point. This effects the amplitude and the characteristic frequency of the acoustic pulse. The pulse amplitude is linear in the energy. Using ref. 1, eqns. (18) and (40) we may write the maximum pressure amplitude as:

$$|P_m| = \frac{\beta\, c^2\, E_0}{2^{5/2}\pi^{3/2}\, C_p\, \lambda^2\, r} , \tag{1}$$

$$= 3.4 \times 10^{-15} \frac{E_0}{\lambda^2\, r}$$

$$\simeq 6 \times 10^{-7} \text{ dyne/cm}^2$$

where β = 2x10^{-4}/°C = volume expansivity of pure water,
C_p= 2.6x10^{19} eV/gm/°C = specific heat at 20°C,
c= 1.5x10^{5}cm/sec = speed of sound in water,
λ = 36cm = radiation length in water,
r = 4.5x10^{5}cm = observation distance,
E_0= 10^{17}eV = energy deposited by cascade.

Here we have taken the most optimistic case: the particle cascade assumed to be straight downgoing, impinging upon a flat ocean surface, and we take the energy deposition scale as the radiation length for electrons in water. Note the dependance of the maximum pressure upon $1/\lambda^2$. Thus if the cascade hits a rough surface and at an oblique angle, the scale may be as much as 100 times larger and the pressure down by 10^4. This pressure magnitude is not large compared to typical RMS pressure values observed.

The minimum noise in the ocean is due to thermal agitation. This level is reached at high frequencies, but exceeded by orders of magnitude at low frequencies (eg. < kHz). The thermal RMS noise pressure can be written (see Ref.1, Eqn. 50):

$$P_N{}^2 = \frac{2\, \rho\, k\, T\, f^2\, \Delta f}{c} \tag{2}$$

$$P_N \simeq 1.6 \times 10^{-4} \text{ dyne/cm}^2$$

where ρ = 1.0 gm/cm^3 = density of water,
k = 1.38 x 10^{-16} erg/°K = Boltzmann's constant,
T = 400°K = ocean temperature at surface,
$f = c/\lambda$ = 4.17 kHz = central frequency,
$\Delta f \simeq f$ = bandwidth.

One can define a quantity which is close to the optimal signal-to-noise ratio (Ref. 1, Eqn. 27):

$$S/N = \left\{ \frac{\beta}{4\, \pi\, C_p} \right\}^2 \frac{\sqrt{\pi}\, c\, E_0{}^2}{\rho\, k\, T\, r^2\, \lambda} \tag{3}$$

$$\simeq 4 \times 10^{-4} \quad ,$$

using the previously given quantities. This does not look very promissing.

What gains may we hope for? First we may have as much as a factor of 2 from the surface reflection providing a time reversed and inverted pulse (see sketch in figure 1). Next, we surely can obtain a factor of 100 from the addition of pulses from the planned 100 hydrophones in the DUMAND array. (This might be increased to 1000 without significant additional array cost). If we demand a S/N of 10, then the threshold might be as low as 10 eV. A further and possibly substantial gain might be realized from the high frequency noise content of the EAS generated acoustic pulse, but assessment of this must await a detailed calculation. A seemingly unlikely improvement would be from unknown acoustic generation mechanisms (such as the unexplained mechanism observed in the Brookhaven tests).

On the other hand we surely must pay a penalty from geometry at angles other than the vertical, and this, as stated could easily amount to a loss of 100 at large zenith angles. Also, noise in the real ocean is surely greater than thermal. How much worse depends not only upon frequency and weather conditions, but also the arrival angle. At the DUMAND array we are undoubtedly better off than near the surface where we will get noise channeled from great distances. Also noise directed down to the array at steep angles will be local in origin, probably mostly from nearby surface waves. We will have to await actual observations, but I would not be surprised to loose several orders of magnitude to real ocean noise.

Conclusions

Taking the integral cosmic ray primary flux as 10^{-6}/m^2/sr/hr above 10^{17}eV and 10^{-8}/m^2/sr/hr above 10^{18}eV, we arrive at rates of 4400/yr and 88/yr given the acceptance stated earlier. We would similarly expect about 1/yr above 10^{19}eV. It is thus clear that if the threshold for useful EAS energy determination is above 10^{18}eV we will not have a viable experiment. Of course, observation of the high energy muon content of even a few showers at such extreme energies might be revealing of significant changes in the primary interaction. One might also look for anomalous muon content of showers coming from the direction of objects such as Cygnus X-3, though the rates at energies beyond 10^{16}eV do not look promissing.

My final conclusion is that while a tempting idea, it does not appear as though (barring gross error in the calculations above) we are likely to be able to employ acoustic pulse detection of EAS in DUMAND to measure the primary cosmic ray energy. On the other hand it does not seem to be entirely ruled out. The science payoff would be so important that it would seem to be worth further exploration via calculations and perhaps low cost experiment. We will be able to get our first look at the noise situation with the SPS and will be able to study the prospects for the full DUMAND array with the use of the Triad. We should consider the addition of a few more hydrophones to the Triad design to explore this avenue.

Reference

1) J.G. Learned, "Acoustic radiation by charged atomic particles in liquids: An analysis", Phys. Rev. D 19 3293 (1979).

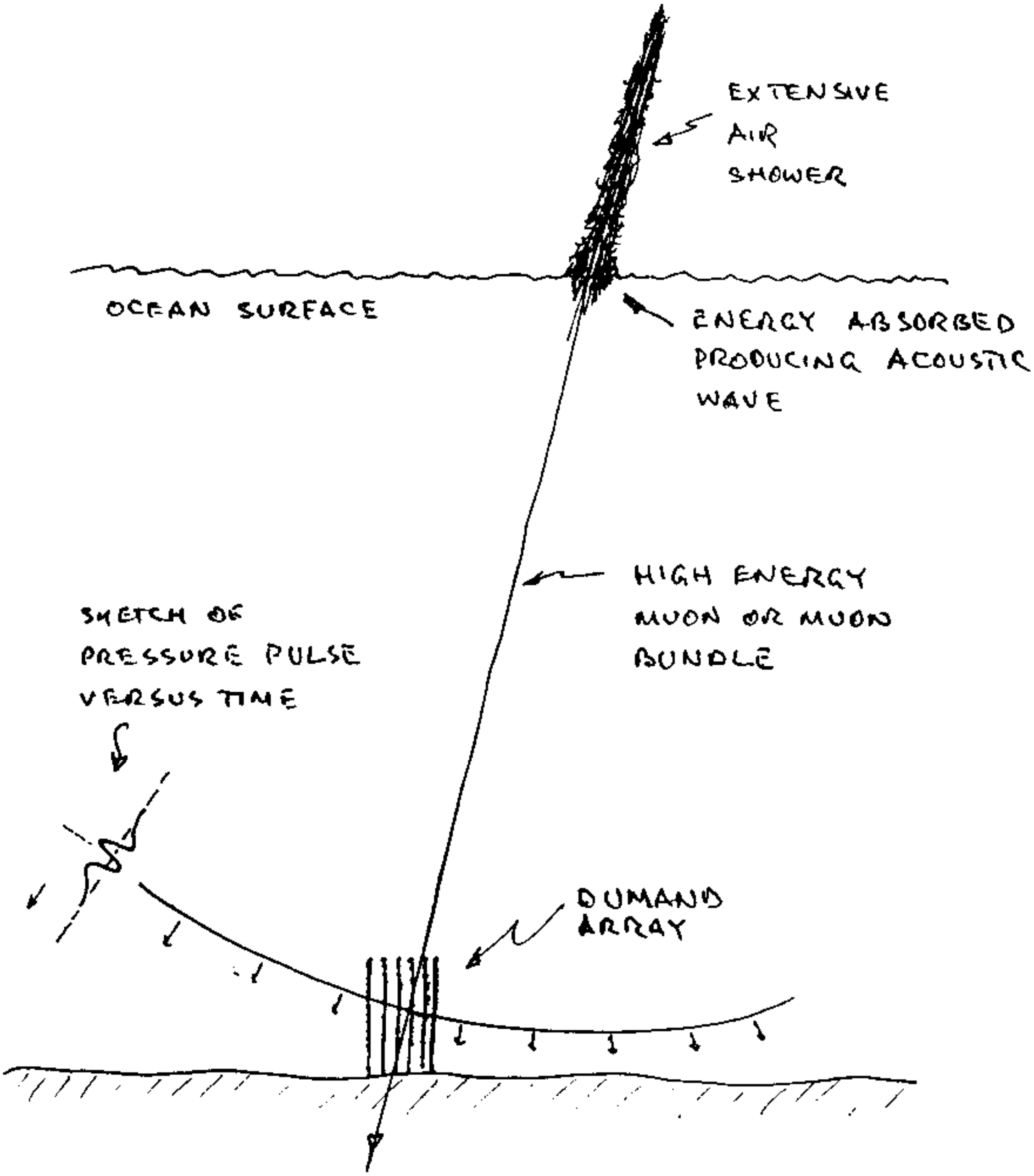

Figure 1

Schematic illustrating the possible use of acoustic waves to measure EAS energy deposition at the ocean surface above DUMAND.